EFFECTS OF HEATING ON MAGNETIC PROPERTIES OF METEORITIC AND LUNAR SAMPLES: APPLICATION TO PALEOINTENSITY STUDIES

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Measurement of the magnetic properties of meteorites and lunar samples at room temperature are relatively straight-forward and unambiguous (Gose and others, 1972; Brecher and Morash, 1974; Nagata and others, 1972, 1974; Watson and others, 1974; Pearce and others, 1974; Fuller 1974; Runcorn and others, 1971; Banerjee and Hargraves, 1972; Brecher and Ranganayaki, 1975; Butler, 1972; Gus'kova, 1963; Herndon and others, 1976; Larson and others, 1973, 1974; Nagata, 1978; Nagata and Sugiura, 1976; Stacy and others, 1961; and Watson and others, 1975).

Almost all studies substantiate the fact that extraterrestrial materials generally contain an easily measurable remanent magnetization, but it is not always clear how the remanence was acquired. In the case of lunar basalts it can be argued that the magnetism is a TRM acquired during initial cooling. However, because nearly all lunar samples are fragments of preexisting rock units disaggregated catastrophically during a meteorite impact event, there exists the real possibility that the original remanence has been modified or largely overprinted during shock events (Fuller, 1974). Brecher (1976) and Brecher and others (1975) have gone so far as to say that all lunar samples have been overprinted to some degree by shock remanent magnetization (SRM). On the other hand, severe shocking can lead to momentary elevation of the rock to temperatures above the Curie points of their contained magnetic phases and can, therefore, lead to TRM or pTRM acquisition during subsequent cooling. Severely shocked lunar breccia, therefore may contain a relatively simple TRM.

If shocking or near-surface heating leads to chemical change in the rock there is always the possibility of the development of chemical remanent magnetization (CRM). In some carbonaceous chondrites it is clear that some of the magnetite has grown by some sort of gas-phase crystallization at low temperature and probably, in the process, acquired CRM. Many carbonaceous chondrites have never been subjected to elevated temperatures and it must be assumed that their remanence must, represent some sort of DRM (Nagata, 1961), IRM, CRM or a combination thereof.

In spite of the many possible mechanisms for remanence acquisition in extraterrestrial materials, most investigators are of the opinion that the remanence in some samples, particularly the high-coercivity portion, is a true TRM. This is based primarily on the character of decay during alternating field (a.f.) demagnetization and the coercivity spectrum. If that is so, then these samples have the potential of providing data from which estimates can be made of the intensity of the ancient magnetic field in which the rocks acquired their magnetism. In many cases, the time of TRM acquisition will correspond to the time of rock origin which can be radiometrically dated.

Valid paleointensity figures, if available, are crucial to the formulation of viable theories concerning the early development of the nebular, solar, and earth-moon systems. Undoubtedly, such estimates represent the most significant magnetic information that can be obtained from extraterrestrial rocks.

Based on the acceptance of TRM in extraterrestrial samples, many workers, using meteorite and lunar samples, have made paleointensity estimates (Collinson and others, 1973; Gose and others, 1973; Banerjee and Mellema, 1974a, 1974b; Collinson and others, 1975; Fuller, 1974; Stephenson and Collinson, 1974; Stephenson and others, 1977; Cisowski and others, 1977; Sugiura and others, 1978; Banerjee and Hargraves, 1972; Butler, 1972; Nagata, 1929; Brecher, 1972; Banerjee and Mellema, 1972; Stacey and others, 1961; Brecher, 1977; Nagata and Sugiura, 1979, Weavery, 1962; Gus'kova, 1963; Gorshkov and others, 1975; Brecher and Ranganayaki, 1975).

For ordinary chondrites, estimates generally range between 0.1 and 0.4 Oe; for achondrites around 0.1 Oe; and for carbonaceous chondrites near 1 Oe. Iron meteorites, for several reasons, appear to be unusable for paleointensity analysis. Nagata (1979) concludes that the postulated values represent likely magnetic fields when the meteoritic material formed about 4.5×10^9 years ago. In the case of the achondrites the field may have been the result of a self-generating dynamo in the metallic core of a primordial planet. In the case of the other meteorites, although somewhat problematical, he suggests that the field may have stemmed from the presence of a primordial solar wind.

Paleointensity estimates of lunar samples range from about 0.015 to 1.5 Oe. In some cases investigation of sub-samples from the same parent sample, by two different research groups, has resulted in greatly divergent estimates.

To date, estimation of paleointensities, both of meteorites and lunar rocks, has principally resulted from application of 1) some form of the Thellier method (Thellier and Thellier, 1959), 2) ARM methods (Banerjee and Mellema, 1974a; Stephenson and Collinson, 1974; Collinson and others, 1973) or

3) NRM vs. IRM (Fuller, 1974). If the remanence is truly a TRM, it would seem reasonable that the Thellier-type methods, involving heating only, would be the most advantageous. Actually, only this technique has been tested through application to historic lava flows (Coe and Grommé, 1973; Khodair and Coe, 1975; Coe and others, 1978, Watson, personal communication, 1977). It is clear from the results that the method does not always work, and, moreover, the reasons for its failure are not always simple to determine. In most cases, some type of chemical alteration (for example, unmixing of magnetic phases, oxidation, reduction, reequilibration of phases) seemed to occur during the various heating and cooling steps to which the sample was subjected.

It was in response to these problems that the ARM method was devised. It has potential utility but has thus far never really been meaningfully tested. Moreover, some critics have raised serious questions concerning the fundamental validity of the method (Levi, 1974; Dunlop and others, 1975) and even some of the people using the method (Collinson and others, 1975) have commented on some of its uncertainties. Moreover, at least one heating step--to high temperatures--is necessary during application of the method.

The method of comparing NRM vs. saturation IRM circumvents some of the problems of the previous two techniques but is capable of providing only a rough order-of-magnitude estimate.

Because the Thellier-type methods have been tested and have been shown to be applicable to some terrestrial rocks, if deleterious effects during heating can be minimized, most paleomagnetists tend to favor this method and put more trust in the results. Unfortunately, meteoritic and lunar samples do not lend themselves readily to the repeated thermal cycling which is necessary with the Thellier technique.

It was in an effort to find ways of minimizing such deleterious thermal effects that we began our investigation under NASA sponsorship in 1971. During the course of our efforts we worked both with meteorites (primarily carbonaceous chondrites) and lunar samples. The work with meteorites was mostly aimed at establishing their opaque mineralogy and developing means of decreasing the adverse effects due to heating, with the hope that these techniques could be applied to thermal experiments involving lunar samples.

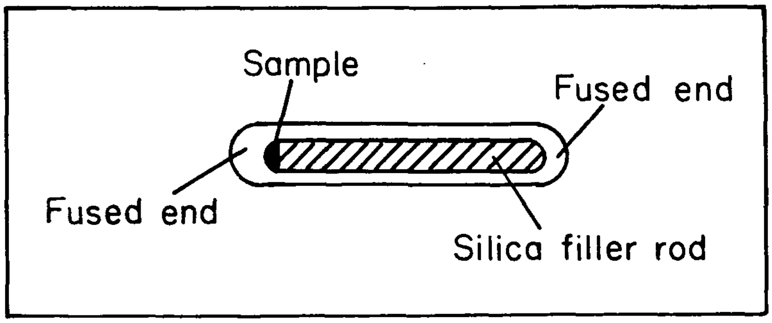
Meteorites

In all, we thermomagnetically examined 41 primitive meteorites of classes C1, C2, C3 and C4 chondrites (Larson and others, 1974; Watson and others, 1975; Herndon and others, 1976) by means of a modified Cahn microbalance (Larson and others, 1975). To reduce the alteration of magnetite iron and nickel-iron grains during measurement of changes in saturation magnetization with temperature (J_s-T), we flowed a mixture of H_2 and CO_2 (in an N_2 carrier gas) past the sample. The particular oxygen fugacity (fO_2) of the gas mixture could be varied in real time by changing the proportions of H_2/CO_2. The fO_2 could be monitored during the experiment by measuring the voltage put out by an yttria-doped zirconia tube placed adjacent to the sample, a method previously developed by high-temperature experimental chemists (Sato, 1971; Nafziger and others, 1971). For safety reasons we did not use pure H_2, but mixed it with N_2, never permitting a mixture richer than 21% H_2. A flow of 21%H_2/79%N_2 was adequate for maintaining iron, nickel-iron, and magnetite in a reducing atmosphere only at temperatures above 300°C. Fortunately, below that temperature reaction rates are relatively slow, except for finely divided material. We were able to demonstrate that this system is far superior to a vacuum for controlling oxidation or reduction during heating of a sample.

In addition, we similarly constructed fugacity-controlled furnaces for use in heatng and cooling samples in a zero or known field (Watson and others, 1974). Since the time of our initial use of fugacity controlled systems, several other paleomagnetists have followed suit. There now are units at Pittsburg University (Schmidt), University of Wyoming (Shive), and Toronto University (Strangway).

It became apparent, however, through our work on meteorites and synthesized samples, that gas-mixing at one atmosphere pressure is ineffective in controlling the breakdown of high-vapor-pressure constituents like troilite (FeS). During heating, troilite, particularly if finely divided, dissociates; sulfur leaves the system and iron (or iron oxide) forms (Larson and others, 1974; Watson and others, 1975; and Herndon and others, 1976). Breakdown can begin just above 100°C if the troilite grain size is very small. That heating can bring about the formation of additional ferromagnetic material was suspected soon after investigation of the first returned lunar rocks when it was found that lunar breccia and soils contain 3 to 4 times the amount of iron found in lunar basalts (Fuller, 1974). Houslay and others (1973) and Pearce and others (1972) considered the iron to result from reduction of iron-rich silicate glass formed during meteorite impact. In light of our results, it would seem that iron formation through breakdown of troilite during and following a shock event is a process just as or even more likely than that of reduction of silicate glass.

Our solution to inhibiting FeS dissociation during heating involved encapsulation of the sample in a sealed vessel where pressures developed during the experiment would be sufficient to retard boil off of sulfur. Sealed platinum and gold tubes were found to be difficult to fashion and largely ineffective. Evaporation of several layers of gold on the samples also proved to be inadequate inasmuch as small holes in the coating always persisted. Finally, we tried encapsulation of the sample in a small evacuated silica tube in which, after the sample is introduced, a solid silica rod is fitted into the central tube void, thereby further reducing the volume of the sample chamber (See Figure 1).



Sample encapsulation in silica tube

This method when used in conjunction with gas mixing appears to be a step in the right direction. Alteration of powdered meteoritic troilite, troilite-rich carbonaceous chondrites (for example, Allende) and selected lunar samples have been essentially eliminated by application of this procedure prior to $_s$-T analysis. Interestingly enough, even though the tube is closed, it is possible for the gas environment surrounding the tube to affect the oxygen fugacity. For example, a lunar sample previously heated in air to 200°C during measurement of its dielectric properties was encapsulated and examined by J_s-T analysis. A considerable component of magnetite

(T_c=580°C) was at first noticeable in the analysis. Flowage of 21%H_2/79%N_2 only, reduced the Fe_3O_4 to iron. Subsequently, the gas mixture was relatively enriched in CO_2 and magnetite again became detectable.

A modification of this encapsulation system is now being used in paleointensity experimentation at Toronto University.

By means of J_s-T analysis of encapsulated and unencapsulated samples in a controlled gas-buffered atmosphere we were able to determine the major magnetic and potentially magnetic constituents in all 41 carbonaceous chondrites we obtained. Moreover, by calibration of the balance, we were able to accurately estimate the magnetic saturation moments and subsequently the weight percentages of the magnetic constituents.

Interestingly enough, all C1 chondrites contain only pure magnetite (Fe_3O_4) in amounts that vary from about 8 to 11 wt%. C2 chondrites are variable--some contain only magnetite, some magnetite and iron, and some essentially no magneticmineral. Most, particularly those containing little ferromagnetic material, contain relatively large amouts of fine-grained troilite. C3 and C4 chondrites are also highly varied in their magnetic mineralogic makeup. Some contain only Fe_3O_4, some Fe_3O_4 and troilite, and some Fe_3O_4 and nickel-iron (6-8%Ni).

In view of the variation in physical makeup and opaque and non opaque mineralogy it is probably safe to conclude that the origin of this meteorite group is not simple (Herndon and others, 1976). For that reason, it is suspected that paleointensity estimates, many based on thermal studies in which gas control and encapsulation were not used, are generally questionable reliability. For those samples that contain large amounts of fine-grained troilite, standard Thellier type experiments would be nearly hopeless. For these, irreversible breakdown of FeS to Fe_3O_4 or Fe begins near 100°C and progressively increases with temperature. Butler (1972) and Banerjee and Hargraves (1972) attempted to use thermal techniques on the C3 Allende meteorite but were forced to discontinue their experiments at temperatures of 150°C and 130°C, respectively, because of deleterious breakdown effects. They nonetheless made estimates of the paleointensities on the basis of the low-temperature portion of the demagnetization-remagnetization plot. Low-temperature components such as these could have had a variety of modes of remanence acquisition and therefore the paleointensity estimates are highly suspect.

According to Nagata (1979) the most reliable paleointensity estimates are derived from analysis of the extremely stable remanence in Cl chondrites. Yet, these are non equilibrium mixtures of exterrestrial debris which has undergone minimal heating, metamorphism, and compaction. As is evident from their volatile and mineralogic makeup they appear to have undergone little or no heating above 100°C. Their remanence can hardly be termed TRM but must be some admixture of DRM, CRM and even IRM. All paleointensity studies of Cl chondrite assume that the remanence is a TRM. Likely, the results to date are essentially meaningless.

Lunar Studies

Reliable paleointensity estimates based on analysis of lunar rocks no doubt constitute the potentially most-significant information obtainable by the paleomagnetic community. However, lunar samples, like meteorites, are very difficult rocks to work with during thermal experiments. They contain variable proportions of iron, nickel-iron, troilite, ilmenite, chromium ulvo spinel, and titanium chromite, in an unknown state of equilibrium. If deleterious effects during heating are to be avoided it is now clear that they must be encapsulated and subsequently heated in a gas-buffered furnace. Unfortunately many (probably most) of the published paleointensity estimates are based on studies in which alteration safeguards were minimal: samples were simply heated in air or in vacuum. It is no wonder that the intensity estimates are so contradictory.

We have examined a few of the samples used during the early era of paleointensity measurements by the Strangway and Runcorn groups (Larson, 1978). We initially thought that degraded samples such as these could serve as natural analogues by means of which we could evaluate the most advantageous way of thermally treating samples. We found, by means of petrographic observation, that the degraded samples had been variable but extensively affected by oxidation. Magnetite and even hematite (Fe_2O_3) were common and troilite has suffered breakdown. Even ulvospinel showed oxidational effects. Because of the obvious thermal degradation of these samples, any paleointensity estimates derived from them must be viewed with suspicion.

To test the utility of more sophisticated techniques we encapsulated some of the degraded material and subjected it to J_s-T analysis. Heating to high temperatures (800°C) brought about irreversible changes in the saturation magnetization curves. Some iron apparently alloyed with available elements to produce minerals of highly unusual Curie temperatures and saturation characteristics. Thermal recycling brought about a recquilibration after which no further changes occured. The results of these experiments suggest that thermally degraded samples are not suitable for meaningful paleointensity reexperimentation. They cannot serve as lunar analogues and are, therefore, largely lost to the magnetic community.

It is hoped that in the future, if lunar samples are to be heated, safeguards such as gas mixing and encapsulation will be used, such as is now being done at Toronto University under the guidance of Dr. D. Strangway. Sugiura and others (1978) have reported some of the new attempts at Toronto to estimate the paleolunar field. In these studies they used only gas-mixing fugacity control. Interestingly enough, none of five lunar samples could be shown to contain a reliable high-temperature remanence component and they were unable to make any paleofield estimates. The remanence in several samples disappeared at about 400°C or less and they conclude that this low-temperature component may have been acquired during impact events.

Presently, the Toronto group is additionally using encapsulation and it will be interesting to see what their new results will be.

Possible, at some time in the future, we will be able to perform thermal experiments without overly degrading the sample. At that time, we will have to face the problem of how the lunar rocks acquired their magnetization. for all paleointensity techniques are based on the fundamental assumption that the remanence is solely a TRM. If that is not so, and there are many reasons to question the assumption, then we will have fought hard for a technique that will produce meaningless results.

References

Banerjee, S.K. and Hargraves, R.B., 1972. Natural remanent magnetization of carbonaceous chondrite and the magnetic field in the early solar system. Earth Planet Sci. Lett., 17: 110-119.

Banerjee, S.K. and Mellema, J.P., 1974a. A new method for the determination of paleointensity from the ARM properties of rocks; Earth Planet Sci. Lett., v. 23, pp. 177-184.

Banerjee, S.K. and Mellema, J.P., 1974b. Lunar paleointensity from three Apollo 15 crystalline rocks using an ARM method; Earth Planet Sci. Lett., v. 23, pp. 185-188.

Banerjee, S.K. and Mellema, J.P., 1976. A solar origin for the large magnetic field at 4.0 X 10^9 years ago. Proc. 7th Lunar Sci. Conf., p. 3259-3270.

Brecher, A. and Morash, K.R., 1974. Inferences from comparative magnetic studies of some Apollo 17 basalt, breccias, and soils; Abst., paper presented at 5th Lunar Science Conference, Houston.

Brecher, A., Klonowski, M., and Simmons, G., 1975. Magnetic behavior of shocked granodiorities, with reference to lunar rock magnetism (abstract); 6th Lunar Science Conference, Johnson Spacecraft Center, March 1975, pp. 80-82.

Brecher, A. and Ranganayaki, R.P., 1975. Paleomagnetic systematics of ordinary chondrite. Earth Planet Sci. Lett., 25:57-67.

Brecher, A., 1976. Textural remanence: a new model of lunar rock magnetism; Earth Planet Sci. Lett., v. 29, pp. 131-145.

Brecher, A., 1977. Lunar and meteoritic paleomagnetism common origin contested. Nature, 266:381-382.

Brecher, A. and Albright, L., 1977. The thermoremanence hypothesis and the origin of magnetization in iron meteorite. J. Geomag. Geoele., 29:379-400.

Butler, R.F. and Cox, S.V., 1971. Mechanism for producing magnetic remanence in meteorites and lunar samples by cosmic-ray exposure; Science, v. 172, p. 939.

Butler, R.F., 1972. Natural remanent magnetization and thermomagnetic properties of the Allende meteorite. Earth Planet Sci. Lett., v. 17, p. 120-128.

Cisowski, S.M., Hale, C., and Fuller, M., 1977. On the intensity of Ancient lunar fields. Proc. 8th Lunar Sci. Conf., p. 725-750.

Coe, R.S. and Gromme, S., 1973. Comparison of three methods of determining paleointensities; Jour. Geomag. Geoelect., v. 25, pp. 415-423.

Coe, R.S., Gromme, C.S. and Mankinen, E.A., 1978. Geomagnetic paleointensities from radiocarbon-dated lava flows on Hawaii and the question of the Pacific Nondipole Low; Jour. Geophys. Res., v. 83, p. 1740-1756.

Collinson, D.W., Stephenson, A., and Runcorn, S.K., 1973. Magnetic properties of Apollo 15 and 16 rocks; Proc. 4th Lunar Sci. Conf., in Geochim. Cosmochim. Acta. Suppl. 4, v. 3, pp. 2963-2976, Pergamon Press.

Collinson, D.W. Runcorn, S.K., and Stephenson, A., 1975. On changes in the ancient lunar magnetic field (abstract); 6th Lunar science Conference, Johnson Spacecraft Center, March 1975, pp. 158-160.

Dunlop, D.J., Bailey, M.E., and Westcott-Lewis, M.F., 1975. Lunar paleointensity determination using anhysteretic remanence (ARM): A Critique; submitted to Proceedings of 6th Lunar Science Conference, Geochim. Cosmochim. Acta, Pergamon Press.

El Goresy, A. and Ramdohr, P., 1975. Subsobidus reduction of lunar opaque oxides: Textures, assemblages, geochemistry and evidence for a late-stage endogenic gaseous mixture; Proc. 6th Lunar Sci. Conf., p. 729-745.

Fuller, M.D., 1974. Lunar magnetism. Rev. Geoph. Space Phys., 12:23-70.

Gorshkov, E.S., Gus'kova, E.G. and Pochtarev, V.I., 1975. The magnetic investigation of the Sikhote-Alin iron meteorite shower at the site of fall. Meteroritics, 10:9-19.

Gose, W.A., Strangway, D.W., and Pearce, G.W., 1973. A determination of the intensity of the ancient lunar magnetic field; The Moon, v. 7, pp. 196-201.

Gus'kova, Ye.G., 1963. Investigation of natural remanent magnetization of stony meteorites. Geomag. Aeron., 3:308-312.

Gus'kova, Ye.G., 1972. Magnetic properties of meteorites (In Russian). Nauka Press Reningrad, 1-107. English translation, NASA TT F-792 (1976); pp. 1-143.

Herndon, J.M., Rowe, M.W., Larson, E.E., and Watson, D.E., 1972. Magnetism in meteorites: Review of Russian studies: Metoerites, v. 7, p. 263-284.

Herndon, J.M., Row, M.W., Larson, E.E., and Watson, D.E., 1975. Origin of magnetite and pyrrhotite in carbonaceous chondrites; Nature, v. 253, pp. 516-518.

Herndon, J.M., Rowe, M.W., Larson, E.E., and Watson, D.E., 1976, Thermomagnetic analysis of meteorites, 3. C3 and C4 Chondrites; Earth Planet Sci. Lett., v. 29, pp. 283-290.

Housley, R.M., Grant, R.W. and Paton, N.E., 1973. Origin and characteristics of Fe metal in lunar glass welded aggregates; Geochim. Cosmochim. Acta, v. 36, suppl. 3, p. 1065-1076.

Khodair, A.A. and Coe, R.S., 1975. Determination of geomagnetic paleointensity in vacuum; Geophys. Jour., v. 42, pp. 107-115.

Larson, E.E., Watson, D.E., Hernden, J.M., and Rowe, M.W., 1973. Partial A.F. demagnetization studies of 40 meteorites. J. Geomag. Geoelec., 25:331-338.

Larson, E.E., Watson, D.E., Herndon, J.M., and Rowe, M.W., 1974. Thermomagnetic analysis of meteorites, 1. Cl chondrites; Earth Planet Sci. Lett., v. 21, pp. 345-350.

Larson, E.E., Hoblitt, R., and Watson, D.E., 1975. Gas mixing techniques in thermomagnetic analyses. Geophys. Jour., v. 43, pp., 607-620.

Larson, E.E., 1978. Degradation of lunar basalts during thermal heating in vacuum and its relation to paleointensity measurements (Abstr.), Lunar Planet Sci. IX, p. 633, Lunar Planet Institute, Houston.

Levi, S., 1974. Alternating field demagnetization characteristics of some submicron magnetic particles; Trans. Amer. Geophys. Un., EOS, 1p. 1111.

Nafziger, R.H., Ulmer, G.C., and Woerman, E., 1971. Gaseous buffering for the control of oxygen fugacity at one atmosphere; in Research Technique for high pressure and high temperature; ed. G.C. Ulmer; Springer-Verlag, N.Y.

Nagata, T., 1961. Rock Magnetism. Maruzen Publ. Co. Tokyo, pp. 1-350.

Nagata, T., Fisher, R.M., Schwerer, F.C., Fuller, M.D. and Dunn, J.R., 1972. Rock magnetism of Apollo 14 and 15 materials. Proc. Third Lunar Sci. Conf., 3:2423-2447.

Nagata, T., Sugiura, N., Fisher, R.M., Schwerer, F.C., Fuller, M., and Dunn, J.R., 1974. Magnetic properties and natural remanent magnetization of Apollo 16 and 17 lunar materias; Abst., paper presented at 5th Lunar Science Conference, Houston.

Nagata, T. and Sugiura, M., 1976. Magnetic characteristics of some Yamato meteorites-Magnetic classification of stone meteorites. Mem. Nat., Inst. Polar Res. Ser. C., 10:30-58.

Nagata, T. and Sugiura, N., 1977. Paleomagnetic field intensity derived from meteorite magnetization. Phys. Earth Planet Interior, 13:373-393.

Nagata, T., 1979, Meteorite magnetism; paper submitted to the Symposium on Extraterrestrial magnetism.

Pearce, G.W., Williams, R.J., and McKay, D.S., 1972. The magnetic properties and morphology of metallic iron produced by subsolidus reduction of synthetic Apollo 11 composition glasses; Earth Planet Sci. Lett., v. 17, p. 95-104.

Pearce, G.W., Gose, W.A., and Stangway, D.W., 1974. Magnetism of Apollo 17 samples; Abst., paper presented at 5th Lunar Science Conference, Houston.

Pearce, G.W., Hoye, G., Strangway, D.W., Walker, B.M. and Taylor, L.A., 1976. Some complexities in the determination of lunar paleointensities. Proc. 7th Lunar Sci. Conf., p. 3271-3280.

Runcorn, S.K., Collinson, D.W., O'Reilly, W., Stephenson, A., Battey, M.H., Manson, A.J. and Readman, P.W., 1971. Proc. Roy. Soc. London, A 325, p. 157.

Sato, M., 1971. Electrochemical measurements and control of oxygen fugacity and other gaseous fugacities with solid electrolyte sensors; in Research Techniques for high pressur and high temperature; ed. G.C. Ulmer, Springer-Verlag, N.Y.

Shashkanov, V.A. and Metallova, V.V., 1977. Determination of paleointensity from sedimentary and igneous rocks by the method of alternating-field demagnetization. Phys. Earth Planet. Interior, 13:368-372.

Shaw, J., 1974. A new method of determining the magnitude of the paleomagnetic field; application to five historic lavas and five archaeological samples; Geophys. Roy. Astro. Soc., v. 39, p. 133-141.

Stacey, F.D. Lovering, J.F. and Parry, L.G., 1961. Thermomagnetic properties, natural magnetic moments, and magnetic anisotropies of some chondritic meteorites. J. Geophys. Res., 66:1523-1534.

Stephenson, A., Collinson, D.W., and Runcorn, S.K., 1974. Lunar magnetic field paleointensity determinations on Apollo 11, 16, and 17 rocks; Proc. 5th Lunar Sci. Conf., p. 2859-2871.

Stephenson, A. and Collinson, D.W., 1974. Lunar magnetic field paleointensities determined by an anhysteretic remanent magnetization method; Earth Planet Sci. Lett., v. 23, pp. 220-228.

Stephenson, A., Runcorn, S.K., and Collinson, D.W., 1977. Paleointensity estimates from lunar sample 10017 and 10020; Proc. 8th Lunar Sci. Conf., p. 679-687.

Sugiura, N., Strangway, D.W., and Pearce, G.W., 1978. Heating experiments and paleointensity determinations; Submitted to Proceedings of 9th Lunar Science Conference, Geochim. Cosmochem. Acts, Pergamon Press.

Thellier, E. and Thellier, O., 1959. Sur l'intensité du champ magnetique terrestre dans le passé historique et geologique; Ann. Geophys., v. 15, pp. 285-296.

Watson, D.E., Larson, E.E. and Reynolds, R., 1974. Microscopic and thermomagnetic analysis of apollo 17 breccia and basalt: Feasibility of obtaining meaningful paleointensities of the lunar magnetic field; March, 1974, Lunar Science Conference.

Watson, D.E., Larson, E.E., Herndon, J.M., and Rowe, M.W., 1975. Thermomagnetic analysis of meteorites, 2. C2 chondrites; Earth Planet Sci. Lett., v. 27, pp. 101-107.

Weaving, B., 1962. The magnetic properties of the Brewster meteorite. Geophys. Jour., 7:203-211.